Renewable and Sustainable Energy Reviews 15 (2011) 4624–4632

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Preparation and heat transfer characteristics of microencapsulated phase change material slurry: A review

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A R T I C L E I N F O

Article history:
Received 12 March 2011
Accepted 5 July 2011
Available online 14 September 2011

Keywords:
MPCM
MPCS
Preparation
Heat transfer characteristics
Thermal energy storage

A B S T R A C T

Microencapsulated phase change materials (MPCM) have been recognized as effective materials to enhance heat transfer, and to improve heat storage performance in thermal energy system. Microencapsulated phase change material slurry (MPCS) can apply to heat transport and thermal energy storage systems. In order to fully develop the application of MPCS in thermal energy system, more researches on preparation and characteristics of MPCS have been done. This paper presents a review on microencapsulation methods and thermal characteristics of MPCS. It focuses on the thermal properties and heat transfer characteristics of MPCS flowing in horizontal circular pipe. Some phase change materials and microencapsulation methods are analyzed and discussed. Theoretical models for analyzing heat transfer characteristics of MPCS flowing in the pipe are presented. Several factors affecting the heat transfer characteristics of MPCS are also summarized.

Contents

1. Introduction

The demand of energy becomes larger as the rapid development of the economy and human society. At present, energy supply is mainly from fossil fuels. However, conventional fossil fuels are limited, and the use of fossil fuels results in emission of greenhouse gas and many harmful gases, which cause the environmental pollution and climate changes. In recent decades, many researchers do their efforts to deal with these problems. There are three main ways: (1) reduce the energy demand, (2) improve the energy efficiency of power systems and reduce the waste of energy, (3) find new and renewable sources of energy. Thermal energy storage is an effective method that can reduce the mismatch between supply and demand, thus it also improves the energy efficiency of power systems.

Thermal energy storage includes sensible heat storage and latent heat storage. Due to sensible heat storage material has a low-energy storage density, it leads to that heat storage system requires large space to store the materials, and the construction cost also increases. Latent heat storage material provides a high-energy storage density when it undergoes a phase change process, and it is able to store energy at a constant temperature or with a limited range of temperature variation, so phase change materials are widely used in thermal energy storage systems. But the

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doi:10.1016/j.rser.2011.07.090

Nomenclature

c	specific heat (J/kg K)
D	diameter of pipe (m)
d_c	diameter of the core of microcapsules (m)
d_p	diameter of microcapsules (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
Pe	Peclet number
Q	heat of fusion (J/kg)
q'_w	wall heat transfer rate (W)
q_w	wall heat flux (W/m^2)
R	radius of pipe
Re	Reynolds number
Re_x	local Reynolds number
Ste	Stephan number
T	temperature (°C)
T_h	upper phase change temperature (°C)
T_l	lower phase change temperature (°C)
u	axial velocity (m/s)
v	radial velocity (m/s)
Greek letters	
α	volume fraction
α_m	mass fraction
η	viscosity (Pa s)
ρ	density (kg/m^3)
Subscripts	
b	bulk fluid
e	effective
f	carrier fluid
i	inlet
m	mean
o	outlet
p	particle
w	internal wall surface

direct use of phase change materials for thermal energy storage application is limited because the material is prone to be frozen on the application wall when it changes its phase from liquid to solid. Due to the low thermal conductivity of most phase change materials, the frozen layer can drastically decrease the efficiency of heat transfer [1,2]. In order to solve the problem, suspension of the phase change material in a carrier liquid is developed by being emulsified or microencapsulated [3].

Microencapsulation is a process by which particles of solid or liquid material are coated with some polymeric materials. The capsules produced by microencapsulation are in the micrometer to millimeter range. The microencapsulation technology has been widely applied to the pharmaceutical manufacturing, chemical industry and biology engineering. Microcapsules with phase change material as core material are mixed with some carrier fluid, so the suspension is called microencapsulated phase change material slurry (MPCS). The shell of microcapsules protects the core material from interacting with carrier fluid, which enhances the stability of the material and avoids particle aggregation. Microencapsulation increases surface-to-volume ratio of phase change material and the particles interact with particles or fluid, which significantly increases the capability and heat transfer efficiency of MPCS [3,4]. In recent years, researchers have done much work on the preparation and properties of MPCMS, and many important results were obtained.

2. Preparation of microencapsulated phase change materials

The applications of microencapsulated phase change material (MPCM) are mainly in thermal energy storage, heat transfer and temperature controlling. For instance, it is used in the secondary loop of refrigeration system or applied to thermal insulation material in construction. That Narita airport in Tokyo uses MPCMS to store cold energy is a practical large-scale application of MPCS [5]. Griffith and Eamesa [6] applied MPCS in a cooled ceiling system and conducted a four-month experiment. It was proved from the experiment that MPCS could effectively reduce the flow rate while keeping a constant temperature. Mihashi et al. [7] used butyl stearate PCM on porous lightweight aggregates. The concrete impregnated could maintain interior temperature around 18 °C. Tyagi et al. [8] and Zhang et al. [5] present reviews on the development of phase change materials based on microencapsulated technology. Microencapsulated phase change materials are very attractive in improving the thermal performance of textile fabrics [9,10].

Inorganic phase change material has some advantages, such as large thermal conductivity and high energy storage density. However, supercooling is high when the material changes its phase from liquid to solid, and phase separation happens in phase change process. The core material used in MPCM should meet some requirements: (1) suitable phase change temperature or temperature range, (2) large latent heat, (3) good thermal conductivity, (4) low density change and (5) low reactivity. Paraffin is a kind of practical organic material suitable for MPCM. Mixture of organic or inorganic PCM can be used to develop ideal core material.

There are many kinds of organic or inorganic materials which can be used for the shell material. However, polymers are commonly used. The shell material should be selected according to the physical properties of the core material. If the core material is hydrophilic, hydrophobic polymer is generally used as the shell material, and vice versa. The shell material should meet some requirements [11]: (1) good flexibility, (2) good sealing tightness, (3) endurance and (4) low reactivity. Some polymers are often selected as shell material, such as polystyrene, polymethylmethacrylate, Arabic gum, gelatin, amino plastics, gelatin-gum Arabic, urea formaldehyde resin, melamine formaldehyde resin, gelatin formaldehyde resin, and so on [9,12–16]. The silica prepared by hydrolysis condensation reaction of TEOS is also used as shell material [17].

Microcapsules can be achieved by many methods, which include physical method, chemical method and physicochemical method. Microencapsulation methods of phase change materials are presented in Table 1. The diameter ranges of microcapsules are shown in Table 2 [31].

- *Physical methods*: Spray drying, spray cooling, air suspension coating, supercritical fluid method, centrifugal extrusion, electrostatic precipitation, and so on.
- *Chemical methods*: Interfacial polymerization, in situ polymerization, piercing-solidifying, suspension cross-link method, and so on.
- *Physicochemical method*: Phase separation.

Fig. 1 presents type of microcapsules, such as mononuclear microcapsules: a single core wrapped with a continuous shell material, poly-nuclear microcapsules: many cores coated with a continuous shell material and multi-film microcapsules: a

Table 1
Microencapsulation methods of phase change materials.

References	Core material	Shell material	Microencapsulation method
Zou et al. [18]	Hexadecane	TDI and EDA	Interfacial polymerization
Fang et al. [17]	Paraffin wax	SiO_2	Sol–gel method
Chen et al. [19]	1-Bromohexadecane	Amino plastics	
Ozonur et al. [20]	Coco–fatty acid	Gelatin-gum Arabic	Coacervation
Alvarado et al. [21]	Tetradecane	Gelatin	Coacervation
Choi et al. [22]	Tetradecane	Melamine formaldehyde	In situ polymerization
Alkan et al. [23]	Docasane	Polymethylmethacrylate	Emulsion polymerization
Alkan et al. [24]	Eicosane	Polymethylmethacrylate	Emulsion polymerization
Hawlader et al. [25]	Paraffin wax	Gelatin acacia	Coacervation/spraying drying
Fang et al. [26]	Tetradecane	Urea formaldehyde	In situ polymerization
Zhang et al. [27]	Octadecane	Melamine formaldehyde	In situ polymerization
Bayes-Garcia et al. [28]	Mixture of alkanes	Gelatin-gum Arabic/sterilized gelatin-gum Arabic	Coacervation
Ai et al. [29]	Hexadecane	Polystyrene	Suspension polymerization
Onder et al. [30]	Hexadecane Octadecane Nonadecane	Gelatin-gum Arabic	Complex coacervation

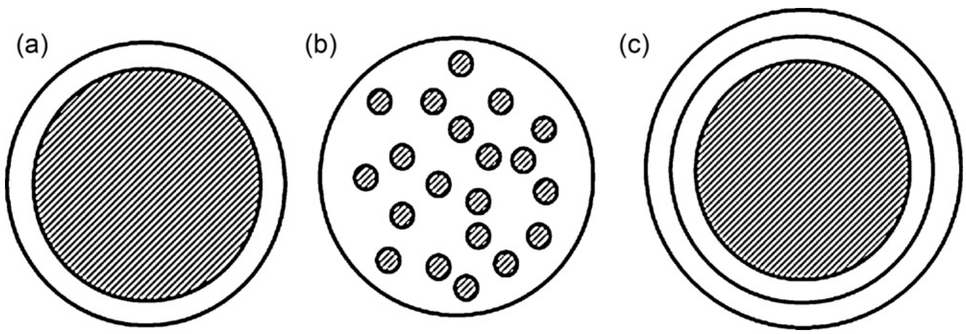


Fig. 1. Type of microcapsules. (a) Mononuclear microcapsule, (b) poly-nuclear microcapsule and (c) multi-film microcapsule.

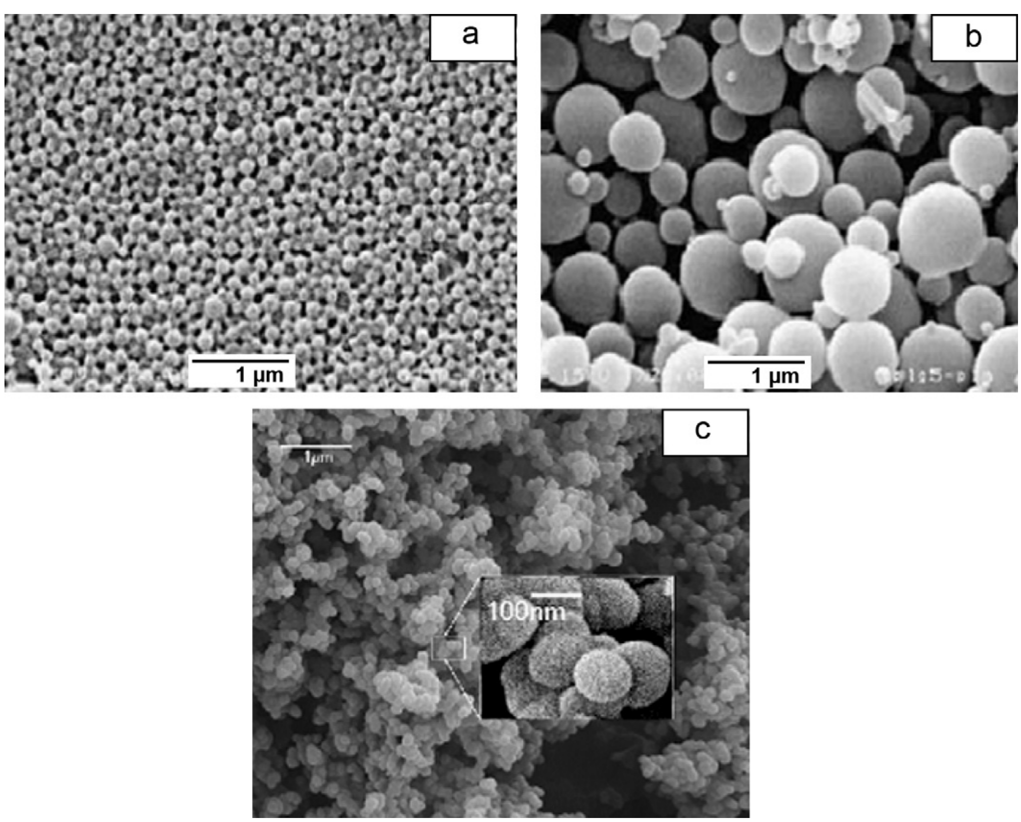


Fig. 2. Microscope profiles of MPCM made by different methods. (a) Spray drying method [25], (b) coacervation method [25] and (c) in situ polymerization method [26].

Table 2
The diameter range of microcapsules [31].

Method of microencapsulation	Core material	Diameter range (μm)
Phase separation	Solid, liquid	2–1200
Interfacial polymerization	Solid, liquid	2–2000
Spray drying/cooling	Solid, liquid	6–600
Centrifugal extrusion	Solid, liquid	1–5000
In situ polymerization	Solid, liquid	1–2000
Suspend wrapping in air	Solid	35–5000
Electrostatic precipitation	Solid, liquid	1–50
Suspension cross-link method	Solid, liquid	2–4000

continuous core coated with multilayer continuous shell material. The microscope profiles of MPCM made by different methods are shown in Fig. 2.

3. Thermal properties of MPCS

The thermal properties of MPCS are different from the PCM and the carrier fluid. In general, several characteristics of MPCS are important for design of MPCS system, such as density, thermal conductivity, specific heat capacity and viscosity.

According to conservation of mass:

$$\rho_p = \frac{1}{\alpha_{m,c}/\rho_c + (1-\alpha_{m,c})/\rho_s} \tag{1}$$

$$\rho_b = \frac{1}{\alpha_{m,p}/\rho_p + (1-\alpha_{m,p})/\rho_f} \tag{2}$$

The densities of microcapsule and carrier fluid are similar to ensure the long-term stability of MPCS while preparing the suspension, so $\alpha_m \approx \alpha$. Though the density of core material varies by 10–15% as phase change process happens, the density of slurry can be analyzed as a constant because the variation is less than 1–2% in low volumetric concentration [32].

The specific heat capacity should be evaluated in order to analyze the phase change effects.

According to conservation of energy in solid phase and liquid phase of PCM:

$$c_p = \alpha_{m,c}c_c + (1-\alpha_{m,c})c_s \tag{3}$$

$$c_b = \alpha_{m,p}c_p + (1-\alpha_{m,p})c_f \tag{4}$$

Though the specific heat capacity is different between solid phase and liquid phase, it can be analyzed as a constant because of the low concentration of PCM.

In the theoretical model, the phase change material is assumed to melt over a temperature range. The specific heat capacity in the melting process is defined as the following equation:

$$Q = \int_{T_l}^{T_h} c\,dT \tag{5}$$

Some works show that the shape of specific heat capacity–temperature curve has a little effect on the heat transfer process [33,34]. Hu and Zhang [35] analyzed four different capacity–temperature curve (left triangle, right triangle, rectangular and sine curve), and the result indicates that four different specific heat capacity–temperature curves have little differences in heat transfer investigation except in the thermal entry region. So the specific heat capacity inside the melting temperature range can be given by the following equation:

$$c_e = c_b + \frac{Q}{T_h - T_l} \tag{6}$$

Therefore the specific heat capacity in the whole process of heat transfer is shown as follows:

$$\begin{cases} c_e = c_b & T_i < T < T_l \\ c_e = c_b + \dfrac{Q}{T_h - T_l} & T_l < T < T_h \\ c_e = c_b & T_h < T < T_o \end{cases} \tag{7}$$

The thermal conductivity of the microcapsules is calculated by the composite sphere approach [36]:

$$\frac{1}{k_p d_p} = \frac{1}{k_c d_c} + \frac{d_p - d_c}{k_s d_p d_c} \tag{8}$$

$$\left(\frac{d_p}{d_c}\right)^3 = 1 + \frac{\rho_c(1-\alpha_{m,c})}{\rho_s \alpha_{m,c}} \tag{9}$$

The thermal conductivity of the MPCS is calculated by Maxwell's relation [37]:

$$k_b = k_f \frac{2 + k_p/k_f + 2\alpha(k_p/k_f - 1)}{2 + k_p/k_f - \alpha(k_p/k_f - 1)} \tag{10}$$

However, the thermal conductivity predicted by Maxwell's relation is lower than the effective thermal conductivity on flowing condition because of the interaction between the particles and fluid. The enhancement of the effective thermal conductivity is relative to the particle size, shear rate, thermal diffusivity, concentration of the slurry, and so on. The effective thermal conductivity can be written as follows [38]:

$$k_e = k_b \bullet f \tag{11}$$

$$f = 1 + B\alpha Pe_p^m = 1 + B\alpha 8^m \left[Pe_f^m \left(\frac{r_p}{r_0}\right)^2\right]^m \left(\frac{r}{r_0}\right)^m \tag{12}$$

$$\begin{cases} B = 3.0 & m = 1.5 & Pe_p < 0.67 \\ B = 1.8 & m = 0.18 & 0.67 \le Pe_p \le 250 \\ B = 3.0 & m = \dfrac{1}{11} & Pe_p > 250 \end{cases} \tag{13}$$

The viscosity of MPCS is important to analyze the flowing process and the pressure drop. The pumping power increases as the pressure drop increases, which is detrimental to the practical application of MPCS. Higher viscosity means higher pumping power and lower turbulence of the slurry, so the heat transfer coefficient may decrease beyond the phase change process. The viscosity of MPCS is affected by several factors, such as the viscosity of carrier fluid, the microcapsules concentration, the particle size and the surface roughness of the microcapsules. Some results [39,40] indicated that the viscosity was 1.2–11 times higher than that of water while the particle concentration increased from 5% to 30%. The MPCS can usually be treated as homogeneous fluid when the volume fraction is not high (up to 37%). The viscosity can be given as follows [41]:

$$\frac{\eta_b}{\eta_f} = (1 - \alpha - A\alpha^2)^{-2.5} \tag{14}$$

where A is a parameter which is relative to the size, the shape, the rigidity and the type of the microcapsules. Mulligan et al. [42] got the value $A = 3.4$ for the MPCS with particle of 10–30 μm in diameter. Wang et al. [40] estimated $A = 4.45$ while investigating the microencapsulated 1-bromohexadecane slurry with particle of 10.112 μm in average diameter at different concentrations. Yamagishi et al. [39] analyzed the microencapsulated octadecane slurry with particle of 6.3 μm in average diameter, and obtained $A = 3.7$. Charunyaorn et al. [38] indicated the value $A = 1.16$ when the volume concentration was lower than 20%.

The MPCS can be treated as Newtonian fluid when the volume fraction is lower than 30% [39]. Yamagishi et al. [43] carried out tests of the MPCS using the microcapsules with the core material of n-tetradecane and n-dodecane. As shown in Fig. 3 [39], the

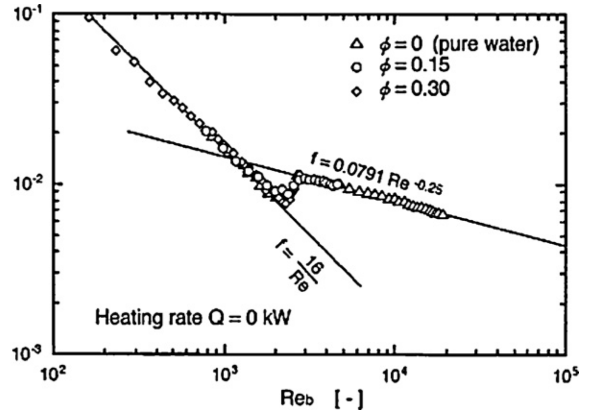


Fig. 3. The relation between friction factor and the Reynolds number of MPCS [39].

relation between friction factor and the Reynolds number of MPCS is presented, and the slurry evidently displays the similar characteristics of Newtonian fluid. Yamagishi et al. [44] indicated that anionic surfactants could decrease the viscosity of MPCS effectively at high mass fraction and suggested that the shape and rigidity of the microcapsules may have an effect on the viscosity. Wang et al. [40] developed experiment to study the rheological behaviors of MPCS, and the result showed that the shear stress increased with shear rate linearly with mass fraction below 27.6%. It is also found that the states of phase change material have nearly no effect on the rheological behaviors, because the particles contacting with the carrier fluid were always solid state. So the viscosity is almost independent of temperature [21,40,43]. Zhang et al. [27] carried out comprehensive studies on the fabrication and properties of microcapsules containing n-octadecane. The result showed that the particle size and morphology were significantly relative to the stirring rate. As the stirring rate increases, the average diameter of particles decreases and the surface of the particle becomes smooth.

For the long-term application, the MPCS should be endurable. Ohtsubo et al. [45] operated several experiments to study why the microcapsules break, and the results presented that the breakage of microcapsules increased while the ratio of particle diameter to thickness increased. Yamagishi et al. [43] indicated that the smaller particle was more endurable by testing the breakage of particles with four different size. Alvarado et al. [21] studied the microcapsules made by microencapsulating n-tetradecane with gelatin, and indicated that the size should be less than 10 μm to ensure the durability of the particles. The experiment also showed the durability increased as particle size decreased. Roy and Sengupta [46] analyzed the stability of some microcapsules of eicosane in the range of 100–250 μm, and the result indicated that the smaller, thicker-walled particles were more stable than the larger, thinner ones. Ai et al. [29] developed a method using casein to protect the microcapsules from breaking in the fabrication process, but the result also showed that the melting temperature increased and the latent heat decreased. Many studies have focused on the thermal and chemical stability of the MPCS when the MPCS is applied practically. Alkan et al. [23] carried out experiments to analyze the stability of MPCS with n-docasane as core material. The result showed that there was no significantly change in the properties of MPCS after 5000 thermal cycles. Ozonur et al. [20] used coco fatty acid mixture as core material to prepare MPCS. It is proved that the chemical structure of the phase change material does not change and the geometric profile of the core material remains the same after 50 cycles. Some other papers have also been published to analyze the thermal and chemical stability of MPCS [18,25,47,48].

4. Heat transfer model of MPCS in the circular pipe

The specific heat capacity is assumed to be a function of the temperature, so the governing equation can be given as follows:

$$u\frac{\partial T}{\partial z} + v\frac{\partial T}{\partial r} = \frac{1}{r\rho_b c_b}\frac{\partial}{\partial r}\left[rk_e\left(\frac{\partial T}{\partial r}\right)\right] \tag{15}$$

The energy equations that govern heat transfer in system are based on the following assumptions: (1) the slurry is a uniform Newtonian fluid, and the physical properties are constant except the specific heat capacity, (2) the flow is fully developed laminar flow, so the radial flow can be neglected, (3) the interfacial thermal resistance of the microcapsules can be neglected, (4) the inlet temperature of the slurry is lower than the upper phase change temperature, (5) the axial conduction and viscous dissipation can be neglected. So, the formulation can be written as:

$$u\frac{\partial T}{\partial z} = \frac{1}{r\rho_b c_b}\frac{\partial}{\partial r}\left[rk_e\left(\frac{\partial T}{\partial r}\right)\right] \tag{16}$$

The boundary conditions are given as follows:

$$T|_{z=0} = T_i \quad \left.\frac{\partial T}{\partial r}\right|_{r=0} = 0 \quad \left.\frac{\partial T}{\partial r}\right|_{r=R} = \frac{q_w}{k_{e,w}} \tag{17}$$

Define the dimensionless temperature, radius and length of the pipe, respectively:

$$\theta = \frac{T - T_i}{q_w R/k_b} \quad r' = \frac{r}{R} \quad z' = \frac{z}{R} \tag{18}$$

The velocity profile of the laminar flow is given as:

$$u = 2u_m(1 - r'^2) \tag{19}$$

$$u_m = \frac{\dot{m}}{\pi r_0^2 \rho_b} \tag{20}$$

The dimensionless governing equation can be written as:

$$Pe_b(1 - r'^2)\frac{\partial \theta}{\partial z'} = \frac{1}{r'}\frac{\partial}{\partial r'}\left[r'f\left(\frac{\partial \theta}{\partial r'}\right)\right] \tag{21}$$

$$Pe_b = Re_b Pr_b = \frac{Du_m\rho_b c_b}{k_b} \tag{22}$$

The dimensionless boundary conditions are given as follows:

$$\theta|_{z'=0} = 0 \quad \left.\frac{\partial \theta}{\partial r'}\right|_{r'=0} = 0 \quad \left.\frac{\partial \theta}{\partial r'}\right|_{r'=1} = \frac{1}{f_w} \tag{23}$$

In the heat transfer process of MPCS in the circular pipe, the phase change material goes through three phases: solid, solid–liquid and liquid, respectively. So the local mean temperature of the MPCS in the whole process is not linear. Choi et al. [49] proposed a "three-region melting model" to calculate the local mean temperature.

$$\text{Region 1 (solid region)}: \ L_1 = \frac{\dot{m}c_b(T_l - T_{m,i})}{q_w}L \tag{24a}$$

$$\text{Region 2 (phase change region)}: \ L_2 = L - L_1 - L_3 \tag{24b}$$

$$\text{Region 3 (liquid region)}: \ L_1 = \frac{\dot{m}c_b(T_{m,o} - T_h)}{q_w}L \tag{24c}$$

The local mean temperature can be given as:

$$\begin{cases} T_m = T_i + \dfrac{T_l - T_{m,i}}{L_1}z & 0 \le z \le L_1 \\ T_m = T_l + \dfrac{T_h - T_l}{L_2}(z - L_1) & L_1 \le z \le L_1 + L_2 \\ T_m = T_h + \dfrac{T_{m,o} - T_h}{L_3}(z - L_1 - L_2) & L_1 + L_2 \le z \le L \end{cases} \tag{25}$$

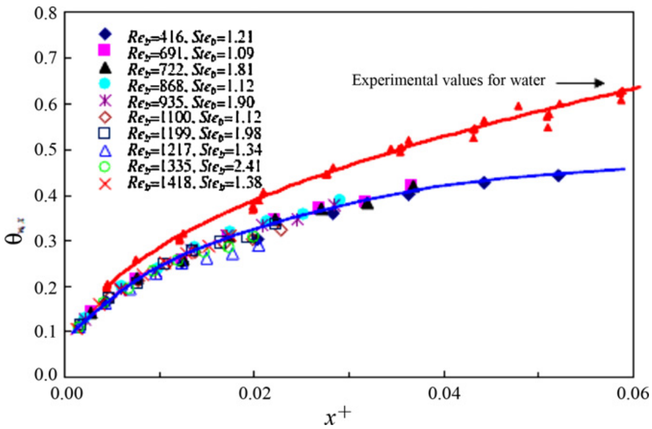


Fig. 4. The variation of dimensionless wall temperature with dimensionless axial length [19].

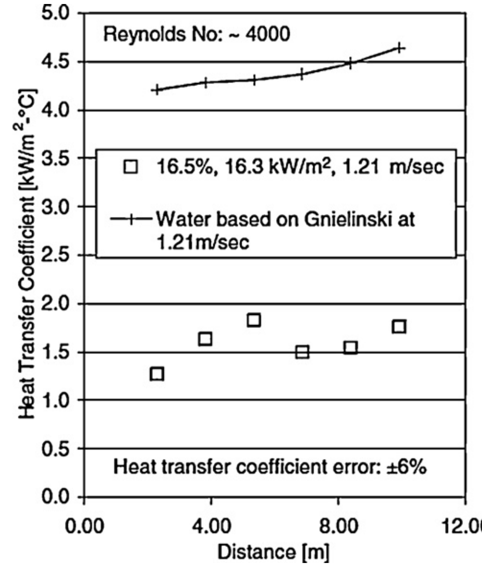


Fig. 5. Heat transfer coefficient with distance [21].

To measure the heat transfer efficiency of MPCS, several parameters are used:

$$\textit{Heat transfer coefficient}:\ h_z = \frac{q_w}{T_w - T_z} \tag{26}$$

$$\text{Local Nusselt number}:\ Nu_z = \frac{h_z D}{k_b} \tag{27}$$

$$\text{Dimensionless local temperature}:\ \theta_z = \frac{T_z - T_i}{q_w R/k_b} \quad \theta_w = \frac{T_w - T_i}{q_w R/k_b} \tag{28}$$

5. Effect of factors on heat transfer characteristics of MPCS

MPCS is advantageous compared to the conventional sensible heat transfer fluid because of the latent heat effect of the phase change material. The specific heat capacity is much higher, which can greatly improve the heat transfer efficiency of the slurry.

In the previous researches, some numerical and experimental analyses were made to estimate the performances of MPCS. Kasza and Chen [3] indicated that the heat transfer efficiency of MPCS could be improved to 3 times than that of the conventional fluid by studying the performance of solar energy or waste heat utilization system with phase change slurry. Charunyaorn et al. [38] carried out a numerical study of the MPCS flowing in the pipe, and the result estimated that the improvement of the heat transfer coefficient can be 4 times higher than that of single phase fluid. Goel et al. [50] conducted experiment to analyze the laminar forced convection heat transfer of MPCS, and the results were compared with that of Charunyaorn et al. [38]. Though the results only agreed qualitatively with the numerical ones and the difference was about 45%, those indicated that the dimensionless wall temperature could be 50% reduction to that of single phase fluid. Zhang and Faghri [51] analyzed the results of Charunyaorn et al. [38] and Goel et al. [50] and pointed out the supercooling was the most important reason to result in the difference. Chen et al. [19] developed an experiment to analyze the performance of the MPCS formed by microencapsulating industrial grade 1-bromohexadecane as phase change material. As shown in Fig. 4, the decrease of the dimensionless internal wall temperature for 15.8 wt% MPCS could be 30% higher than that of water. Choi et al. [49] studied the phase change emulsion in turbulent flow under constant heat flux. The result indicated that heat transfer coefficient of the emulsion increased in region 1, decreased in region 2 and increased again in region 3. Several experiments of thermal performance of MPCS showed similar results [21,39,40], which is presented in Fig. 5 [21]. Alvarado et al. [21] estimated that the heat transfer coefficient reached the maximum near the melting point. Wang et al. [52] carried out experiments to investigate the heat transfer performances of MPCS in a circular horizontal tube with constant heat flux at both laminar and turbulent flow conditions. It is found that the heat transfer coefficients for laminar flow are always higher than that of single phase fluid. The average Nusselt number of turbulent slurry can be 2.5 times higher than that of water. Two heat transfer correlations were also proposed based on the experimental data to describe the performances of MPCS at laminar flow and turbulent flow conditions, respectively. Ozonur et al. [20] designed experiments to study the heat transfer rate of the microencapsulated phase change material and the pure phase change material (coco fatty acid). The result showed that the heat transfer rate of microencapsulated phase change material was higher compared to that of pure phase change material during charging process.

Hu and Zhang [35] presented a numerical analysis of convective heat transfer enhancement with MPCS. It is modified to define the local Nusselt number because the conventional local Nusselt number which is used to describe the single phase fluid cannot accurately describe the performance of MPCS. The energy equation is analyzed and the result shows that the modified local Nusselt number is a function of several parameters, such as Re, Pr, specific heat, the uniformity of velocity profile and the dimensionless temperature gradient. But the parameters are not independent and some are strongly relative to the properties of microcapsules and MPCS. However, they made numerical simulations and predicted that *Ste* number and mass fraction were the most important parameters affecting the heat transfer enhancement. The supercooling, phase change temperature range, the particle size and the Re number have influence on the heat transfer performance. Zhao et al. [53] made parametric analysis of enhanced heat transfer for laminar flow of MPCS in a circular tube with constant wall temperature. It indicated that the result is similar to that of Hu and Zhang [35]. Six parameters such as *Ste* number, volume fraction, supercooling, phase change temperature range, ration of particle size to tube radius and Re number are relative to the performance of MPCS, and the *Ste* number, volume fraction and particle size are the most important.

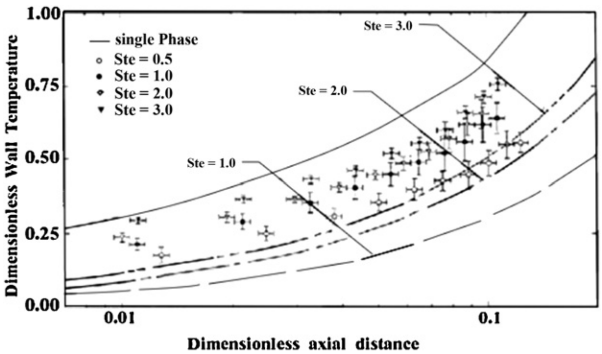


Fig. 6. Effect of *Ste* on dimensionless wall temperature [50].

5.1. Effect of Ste number on heat transfer characteristics of MPCS

The *Ste* number is a dimensionless number to present the ratio of the sensible heat to the latent heat, which is given as $Ste = c_e(q_w r/k_b)$. The influence caused by *Ste* is strongly dependent of the phase change process. Charunyaorn et al. [38] carried out a numerical study of the MPCS and pointed out that the *Ste* number was the most important parameter affecting the heat transfer process. Goel et al. [50] carried out experiment under laminar flow and constant heat flux, and the data also showed that *Ste* number was the most important parameter, especially for *Ste* less than 1.0, as shown in Fig. 6. Zeng et al. [54] developed an experiment to study the heat transfer characteristics of MPCS in laminar flow, and the result showed *Ste* number was the most dominant parameter to affect the local Nusselt number. Zhang et al. [55] carried out theoretical analysis of convective heat transfer enhancement of MPCS. The numerical simulation results presented that the fluctuation amplitude and range increase as the *Ste* number decreases in the region 2. Chen et al. [19] indicated that the expression $Ste = c_e(q_w r/k_b)$ could not show the sensible heat in the heat transfer process, so a new *Ste* number was defined as:

$$Ste = \frac{c_e(T_o - T_i) - Q}{Q} = \frac{q'_w}{\dot{m}Q} - 1 \tag{29}$$

5.2. Effect of mass fraction on heat transfer characteristics of MPCS

The mass fraction affects the thermal conductivity and the viscosity of MPCS according to Eq. (10). Mulligan et al. [42] carried out experiments to study the properties of MPCS with n-octadecane, n-eicosane, n-heptadecane and n-dodecane as core material. It is found the diameter of microcapsules is between 10 and 30 μm and the specific heat increases significantly as mass fraction increases. Yamagishi et al. [43] conducted several experiments under turbulent flow with MPCS of which the size was from 2 to 10 μm. The results showed that the performance of the slurry changed from turbulent flow to laminar flow at high mass fraction and the pressure drop decreased. Experimental data of Yamagishi et al. [39] shows that heat transfer coefficient increases with mass fraction at the same Re number (as shown in Fig. 7), and decreases with higher heating rate. The experimental results of Inaba et al. [57] indicated that the ratio between heat transported and pumping power decreased while increasing the mass fraction of large sized particles at laminar flow condition.

5.3. Effect of Re number on heat transfer characteristics of MPCS

Re number presents the turbulence of MPCS which can improve or suppress the heat transfer coefficient. Roy and Avanic [56] experimental results indicate the Re number has a significant effect on heat transfer performance with phase change material emulsions. Inaba et al. [57] conducted experiments to study the MPCS with large sized particles of high mass concentration. The results showed that the pressure drop decreased at turbulent flow and increased at laminar flow. Numerical analysis of convective heat transfer enhancement with MPCS at laminar flow condition of Hu and Zhang [35] indicated that the average Nu number increased with increasing Re for the same heat transfer fluid. Zeng et al. [54] indicates that the dimensionless wall temperature decreases as Re increases at the same dimensionless length.

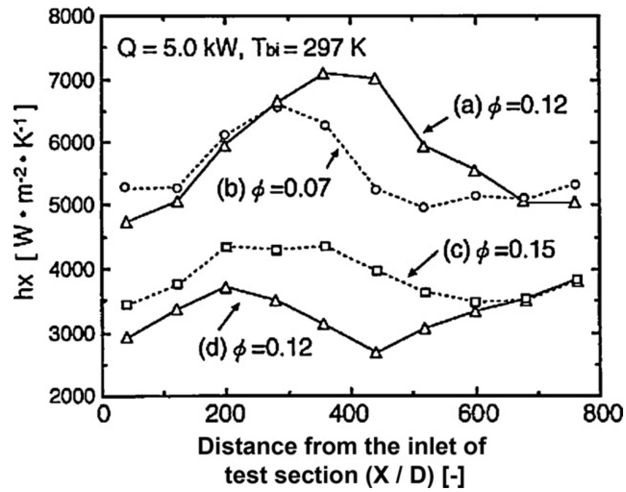


Fig. 7. Local heat transfer coefficients of MCPCM slurries for different Reynolds numbers [39]. (a) $Re_z = 9311–11{,}020$; $c = 0.12$, (b) $Re_z = 11{,}094–12{,}962$; $c = 0.07$, (c) $Re_z = 5294–6329$; $c = 0.15$ and (d) $Re_z = 5488–6495$; $c = 0.12$.

5.4. Effect of supercooling and phase change temperature range on heat transfer characteristics of MPCS

Supercooling is the temperature difference between freezing and melting points. Researchers explain the supercooling with the classical nucleation theory which indicates that the phase change process happens because of the homogeneous or heterogeneous nucleation mechanism. Montenegro et al. [58] found that homogeneous nucleation mechanism caused greater supercooling. Some experimental results show that heterogeneous nucleation is preferred to avoid undesirable supercooling [43,59]. The numerical analysis of Hu and Zhang [35] estimates that the heat transfer enhancement increases as the supercooling and phase change temperature range decrease. Yamagishi et al. [43] carried out experiments and indicated that supercooling and the phase change temperature range increased as the particle size was less than 100 μm, and it was presented that using nucleating agents with molecular structure similar to the core material could considerably suppress the supercooling. Alvarado et al. [21] prepared MPCS with microcapsules containing 94% tetradecane and 6% tetradecanol, and the experimental data indicated that the supercooling significantly decreased. However, the latent heat of fusion decreases significantly as nucleating agent concentration increases [60]. Fan et al. [61] conducted experiment to study the properties of MPCS with octadecane as core material and sodium chloride, octadecanol and paraffin as nucleating agents, respectively. The results show that the supercooling decreases significantly when the nucleating agent increases at proper concentration. Zhang et al. [55] indicates that the fluctuation amplitude increases with decreasing phase change temperature range when phase change happens.

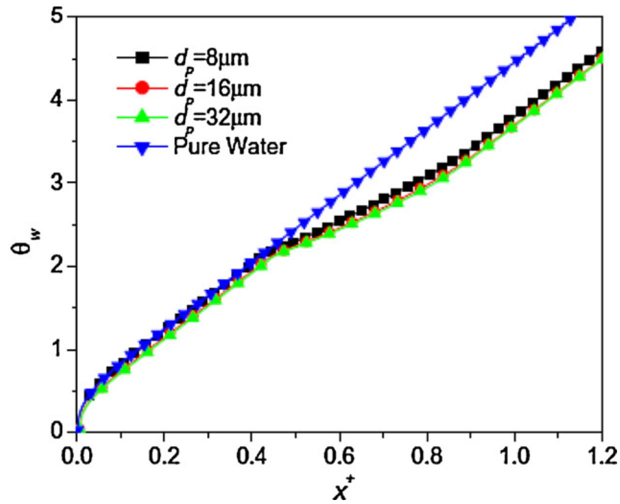


Fig. 8. Dimensionless wall temperature for different particle size [54].

5.5. Effect of particle size on heat transfer characteristics of MPCS

The particle size is also relative to the thermal conductivity of MPCS according to Eq. (8). In previous researches, Hetsroni [62] indicated that the particles size affected the heat transfer by enhancing or suppressing the turbulence of the slurry. Liu et al. [63] analyzed the relation of heat transfer coefficient with the size of particles added into single phase fluid. The results estimated that there was a critical size, and when the particles were larger than the critical size, the heat transfer coefficient would be enhanced, and vice versa. Roy and Avanic [56] carried out an experiment to study the laminar heat transfer with phase change material emulsion. The results show the characteristics are similar to MPCS, suggesting that the shell of particle seems to have no significant effect on heat transfer process. Inaba et al. [57] analyzed MPCS with different sized particles. The results indicate that the heat transfer performance of MPCS with different size is better than that of single sized ones. The experimental results of Zhang et al. [27] presented that the particle size had no effect on the melting behaviors of microcapsules, but significantly affected the freezing behaviors. Zeng et al. [54] results showed that the effect caused by particle size was independent of phase change, and the dimensionless wall temperature decreased as the particle size increased, which is shown in Fig. 8.

6. Conclusions

A review of MPCS used for heat transfer in a circular tube has been carried out in this paper. The materials, fabrication and properties of MPCS are presented. The microencapsulation technology is very useful to apply phase change materials into thermal storage and heat transfer field. The heat transfer characteristics and parameters affecting the heat transfer process are shown, which provides some basic information on the research of MPCS. The previous researches prove that the MPCS makes the heat transfer coefficient improving. However, more work need to be done for developing the practical application of MPCS.

Acknowledgement

The authors thank the National Natural Science Foundation of China (Grant No. 50776043) and the Fundamental Research Funds for the Central Universities (Grant No. 1114020401) for financial support of this research.

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